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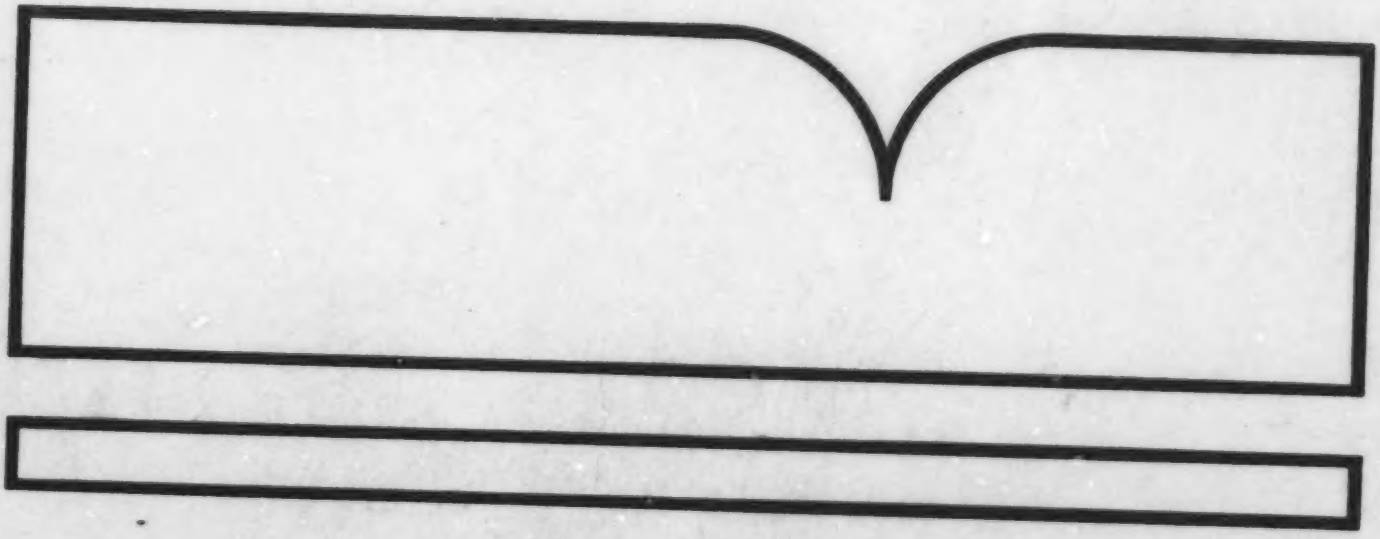
Storm and Combined Sewer Storage Treatment Theory Compared to Computer Simulation

Charles Howard and Associates Ltd.
Vancouver (British Columbia)

Prepared for

Environmental Protection Agency
Cincinnati, OH

Jul 81



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STORM AND COMBINED SEWER STORAGE TREATMENT THEORY COMPARED TO COMPUTER SIMULATION

by

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Grant No. R-805109

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TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA-600/2-81-125	2. ORD Report	3. RECIPIENT'S ACCESSION NO. PB81 222341
4. TITLE AND SUBTITLE "Storm and Combined Sewer Storage Treatment Theory Compared to Computer Simulation"		5. REPORT DATE July 1981
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) C. D. D. Howard, Paul E. Platt, Uri Shamir		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Charles Howard & Associates Ltd. 528 St. James Street WINNIPEG, Manitoba R3G 3J4		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. R805109
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cinti, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final, 7/77 -- 10/79
		14. SPONSORING AGENCY CODE EPA/600/14
15. SUPPLEMENTARY NOTES Project Officer - Richard Field - Phone: 201/321-6674 - FTS: 340-6674		

16. ABSTRACT

In the field of storm water management there is a need for a wide range of evaluation techniques ranging from complex to simple. To compliment detailed simulation techniques, so called mathematical or statistical techniques have been developed. Although complex in development, the statistical techniques are quick and simple to apply.

This volume presents a comparison between two statistical techniques, a statistical analytical and a statistical moments method. The basis of comparison between the two methods is their ability to reproduce results obtained from detailed simulation.

The comparisons for 5 U.S. cities indicate that both procedures exhibit apparent strengths and weaknesses. This volume provides basic information required to use either procedure.

This report is submitted as part of Grant No. R-805109 by Charles Howard and Associates Ltd. under sponsorship of the U.S. Environmental Protection Agency. Work was completed in October, 1979.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Storm Sewers, *Water pollution control simulation, *Sewage Treatment, *Surface water runoff, *Runoff, *Combined sewers, *Mathematical models, Storage tanks, Methodology, *Separate sewers, *Statistical Methodology	Simplified Evalution Preliminary Evaluation	13B
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 58
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory developes new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment for public drinking water supplies and to minimize the adverse economic, social, health, and esthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the research and the user community.

This report describes and compares three techniques for preliminary screening of storage and treatment combinations for urban stormwater pollution control. These comparisons, when interpreted with an understanding of the assumptions involved, will help in deciding which methods are appropriate for a particular application and will help lead to economically optimum solutions to urban stormwater pollution problems.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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ABSTRACT

In recent years mathematical techniques have been developed to reduce the amount of computer work necessary in the analysis of stormwater management systems. These techniques provide greater insights into the behaviour of storage in regulating urban runoff and present opportunities for rapidly screening out costly or ineffective alternatives. One technique is the statistical analytical (SA) method; another is called the statistical moments (SM) method. Both of these methods use the statistics of various rainfall characteristics to directly determine the level of runoff and pollution control which a specified combination of storage and treatment will provide. The mathematical derivations are somewhat complex but the results are simple and easily applied in the form of nomograms or programs for hand calculators or desk-top computers.

Until these techniques were developed the only method for developing the same information was by continuous simulation using a long record of rainfall events. The computer program, STORM, is a widely used program of this type. Such simulations are not inexpensive when a large number of alternatives are to be investigated. Comparisons between simulation and statistical results are useful in providing a measure of confidence in the statistical techniques. At the same time, the simulation results themselves do not represent an absolute truth as they are affected by the period of record simulated. The mathematical techniques provide a simply way to plan and subsequently to check the results of such computer simulations and to ensure that some possibly promising alternative has not been overlooked.

This volume presents a comparison between two statistical techniques, a statistical analytical and a statistical moments method. The basis of comparison between the two methods is their ability to reproduce results obtained from detailed simulation.

The comparisons for 5 U.S. cities indicate that both procedures exhibit apparent strengths and weaknesses. This volume provides basic information required to use either procedure.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

SA	Statistical Analytical Method
SM	Statistical Moments Method
STORM	Storage, Treatment, Overflow and Runoff Model
BOD	Biochemical Oxygen Demand
USEPA	United States Environmental Protection Agency
Jn. E.E.	Journal of Environmental Engineering
WRR	Water Resources Research
pdf	Probability density function

SYMBOLS

a	Coefficient in isoquant equations and % deviation of SA from ST and in equation for treatment in storage
AR	Annual runoff volume (inches/year)
b	Coefficient in isoquant equations and % deviation of SM from ST and in equation for treatment in storage
β	Reciprocal of event average intensity
β'	Reciprocal of average runoff intensity
B_e	Inter-event times (also b) for rainfall
B_r	Inter-event times for runoff
$\overline{B}_s$	Reciprocal of average inter-event time for storage utilizing events
CR	Runoff coefficient
C_R	Average annual percent runoff control
C_p	Percent pollution control
d	Coefficient in isoquant equation
D	Duration
e	Actual evapotranspiration rate
EXP	Exponentiation
f	Coefficient in isoquant equations
G	Probability mass function

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H	Total number of hours in the rainy season
I	Percent imperviousness
I_e	Average intensity of an event
$\overline{I}_1$	Average intensity for events with intensities less than Ω
$\overline{I}_\Omega$	Average treatment rate
k	A constant
K	Treatment rate capacity factor
K_o	Modified Bessel function of the second kind of order 0.
λ	Reciprocal of average rainfall event duration
λ'	Reciprocal of average runoff event duration
m	Rate of moisture deficit increase
m_x	Maximum moisture deficit
n	Number of events
n_r	Average annual number of runoff events
η_Ω	Treatment plant efficiency
η_s	Efficiency of treatment process in storage
η	Overall efficiency of treatment in storage and plant
o	Subscript referring to overflows
p	Overflow from storage
P	Average annual precipitation
$\overline{P}'$	Average annual net precipitation volume
P_u	Average annual volume of overflows
Prob	Probability
q	Subscript referring to runoff
Q	Total flow rate
r	Subscript referring to rainfall except in n_r
R	Percent runoff control and average annual runoff
RT	Retention time
RTMIN	Reasonable minimum residence time
R_1	Percent pollution control
s_d	Depression storage
S	Storage capacity

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t	Time
τ	Minimum duration of a dry period (sample interval)
T	Wet-weather treatment rate (inches/hour) in isoquant equations. Also storage operation efficiency in SA method
T_1	Treatment rate at which the Isoquant becomes parallel to the storage axis (inches/hour)
T_2	Treatment rate at which the isoquant intersects the treatment axis (inches/hour)
T_e	Storm event duration
Ω	Treatment plant capacity
v	Unit volume
ν	Coefficient of variations
V_e	Volume of a rainfall event
V_r	Runoff volume
Δ	Average time between storms, SM method
δ	Time between storms
W_R	Mean stormwater loading rate
θ	Average annual number of rainfall events
ϕ	Ratio annual runoff to annual precipitation, runoff coefficient for volumes
ζ	Reciprocal of average rainfall event volume
ζ'	Reciprocal of average runoff event volumes
ζ''	Reciprocal of average storage utilizing event volumes
ψ	Reciprocal of average rainfall inter-event durations
ψ'	Reciprocal of average runoff inter-event durations
ψ''	Reciprocal of average storage utilizing inter-event durations

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ACKNOWLEDGEMENTS

Computer output from the STORM runs of the five major cities was provided by Wayne Huber and James Heaney of the University of Florida. They also reviewed a draft of the report and provided many helpful suggestions for improving the presentation.

Eugene Driscoll and Dominique DiToro of HYDROSCIENCE reviewed the draft and found several places where additional clarification was needed. They also provided a detailed review of the section dealing with their method. It is hoped that all of their comments have been fairly dealt with in the report.

At Charles Howard and Associates Limited, Paul Flatt did the comparative analysis involving STORM and the statistical analytical (HOWARD) method. Uri Shamir provided the statistical moments (HYDROSCIENCE) method calculations and the review of that procedure and he and Paul Flatt prepared the draft report. The final report was prepared by Charles D.D. Howard. Mrs. Anne Peterson's typing and sensitivity to format deserves special acknowledgement.

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SECTION 1

INTRODUCTION

A common problem encountered in the analysis of stormwater management options is to determine how various possible combinations of storage and treatment capacity will effect runoff control. For example, in a combined sewer system it might be desireable to determine how the effectiveness of an existing treatment plant might be improved by providing storage, in various volumes, ahead of the plant. In a storm sewer system which currently consists of undersized pipe capacity it would be desireable to know how the frequency of flooding might be changed by providing various small amounts of storage on the watershed or in the pipes themselves by regulating devices. In a new system it would be desireable to know the combination of storage and pipe or treatment capacity which will provide the desired level of runoff and pollution control at minimum cost. Answers to questions such as these can presently be obtained by three methods:

1. Continuous simulation using a suitable computer program, such as STORM, and a sequence of rainfall events.

2. Mathematically by the statistical moments (SM) method developed by HYDROSCIENCE INC.

3. Mathematically by the statistical analytical (SA) method developed by Charles Howard and Associates Limited.

This report presents a comparison of these three methods for preliminary screening of storage-treatment combinations. The basis of the comparison is an application of the techniques to assessments for five cities using the actual hourly rainfall data for each. The cities, Atlanta, Washington, Minneapolis, Denver and San Francisco, were selected because they are in different regions of the country and the data have been previously analyzed with the computer program STORM.

The present work develops the required statistical information from the rainfall data, applies both the SA and SM methods and presents the levels of control estimated by all three methods for a wide range of storage-treatment combinations. These results are discussed to explain some possible reasons for discrepancies and to identify the likely relative accuracy of the methods.

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SIMULATION

At the University of Florida the computer program STORM was used to estimate the level of pollutional control for selected combinations of storage and treatment. This work was directed by J.P. Heaney and W.C. Huber and is summarized in a report (1) which is the main source of data for their results. The rainfall data used in this work were obtained and analyzed to develop the statistical parameters required for the SA and SM methods.

Chapter 3 briefly explains the simulation procedure and discusses the way in which the STORM results were used to develop curves of equal pollution control for different combinations of storage and treatment. These curves were called isoquants by Heaney and Huber.

STATISTICAL ANALYTICAL METHOD (SA)

This method was developed by Howard (2) to assist in evaluating results of computer simulations while monitoring technical work under the Canada-Ontario Agreement on Great Lakes Water Quality. The method, which is suited to calculation using a hand-held calculator, has undergone improvements since its original development and is explained in Chapter 4.

The SA method is based on derived probability functions developed from probability density functions for rainfall event durations, volumes and elapsed inter-event time. It uses a simplified model of runoff and storage operations to produce the number and total quantities of overflows from the storage-treatment combination and provides the equations for plotting isoquants like those presented by Heaney and Huber.

STATISTICAL MOMENTS METHOD (SM)

This method, developed by Hydroscience Inc. (5,8) provides information which is similar to that obtained by the SA method but uses a different mathematical development involving the mean and the coefficient of variation of the rainfall data. Chapter 5 briefly describes the SM method.

SCOPE OF THIS ASSIGNMENT

The main purpose of this assignment was to establish the range of validity of the SA method by comparing it to results from STORM computer simulations. Additionally, it was desired to complete the comparison of the mathematical and computer approaches by utilizing the SM method with the same data base. It was not intended to extend any of the work previously done or to attempt any form of calibration to improve agreement among the methods.

The comparisons of results used only those storage-treatment combinations for which the actual computer printout results from STORM runs were available. It is likely that in future, as more experience is gained with similar comparisons, more insight into the applicability of the various methods in different climates and applications will be gained. Furthermore, as these techniques continue to be used it should be possible to further simplify the mathematical approaches to make them better understood by a wider range of users.

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SECTION 2

CONCLUSIONS

TYPICAL RESULTS OF THE DIFFERENT METHODS

Typical results from STORM, the Statistical Analytical and Statistical Moments (Hydroscience) methods are presented in Figures 2.1 and 2.2 for Minneapolis. The Statistical Analytical method indicates higher control than calculated by both STORM and the Statistical Moments method. The comparison is best for relatively low percent control and higher storages.

Table 2.1 contains a comparison of the maximum deviation in degree of pollution predicted by the two statistical methods, as compared to the result from STORM, for each of the five cities. In Table 2.1,

ST = % control from STORM
SA = % control from SA method
SM = % control from SM method.

The maximum is taken over all results obtained for the city.

TABLE 2.1 - Summary of the Maximum Deviations in Percent Runoff Control

City	Maximum Values of:			
	SA-ST	$\frac{SA-ST}{ST} \times 100$	SM-ST	$\frac{SM-ST}{ST} \times 100$
Atlanta	13	33	-10	-83
Denver	16	43	-14	-86
Minneapolis	19	36	-12	-83
San Francisco	19	64	-14	-89
Washington, D.C.	15	36	-11	-73

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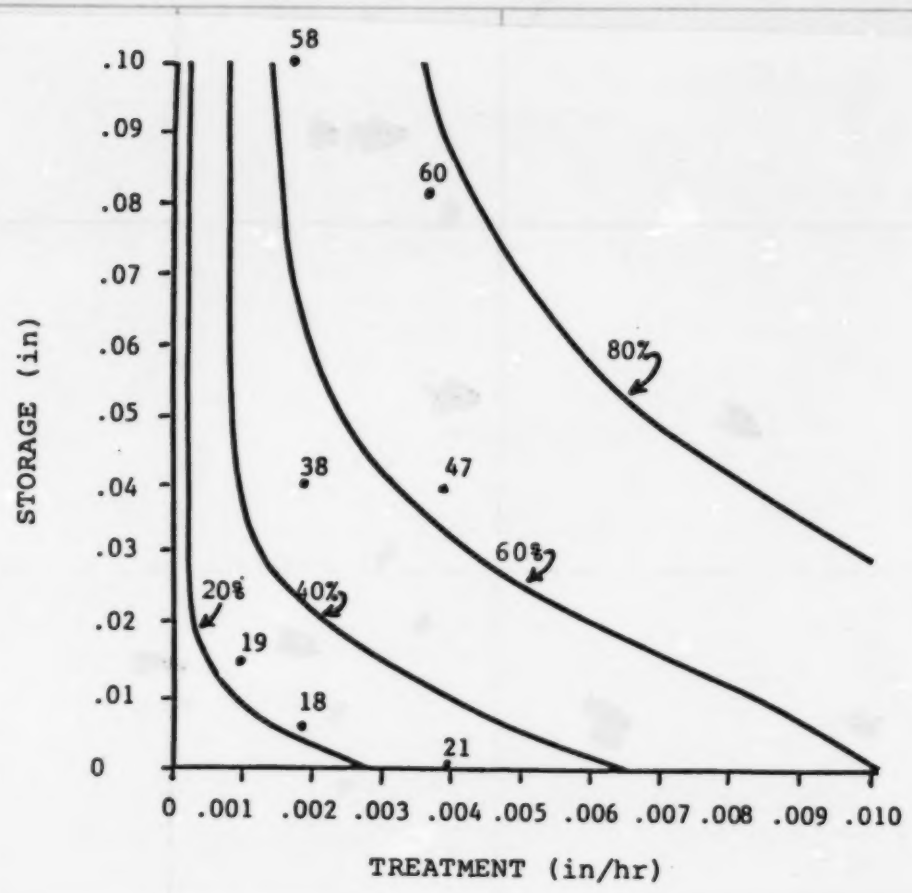

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- • 38 — **% runoff control given by STORM**
- (20% — **20% runoff control isoquant given by Statistical Analytical Method**

FIGURE 2.1 - Comparison of Percent Runoff Control Isoquants from Statistical Analytical Method with Results from "STORM" - Minneapolis

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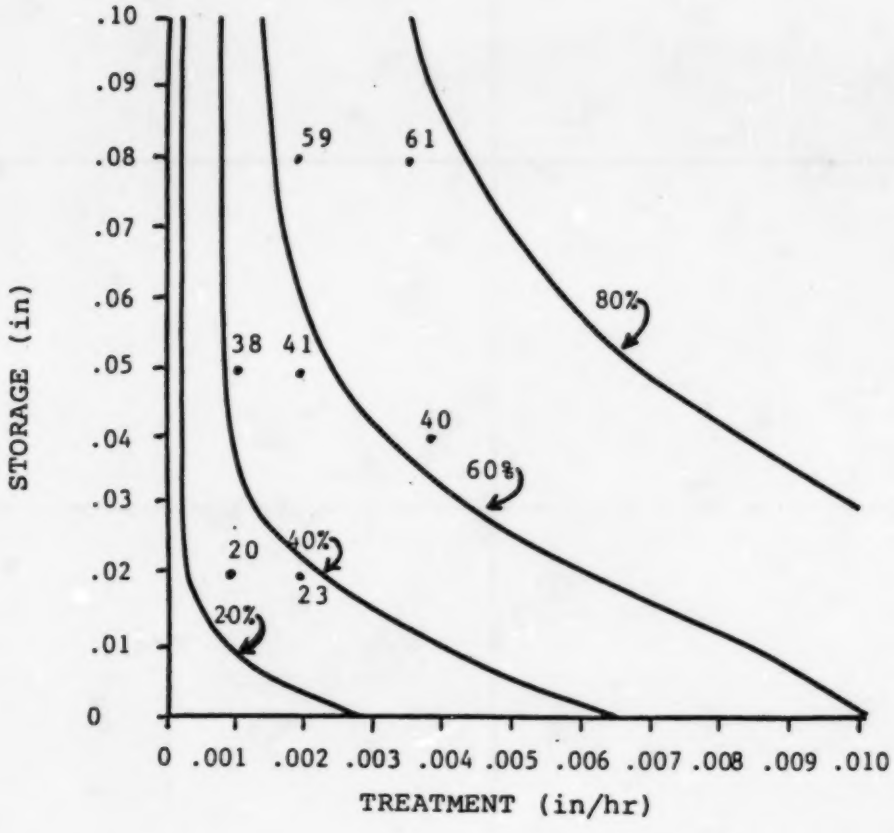

LEGEND

• 38 — % runoff control given by Hydroscience Statistical Moments Method

20% — 20% runoff control isoquant given by Statistical Analytical Method

FIGURE 2.2 - Comparison of Percent Runoff Control Isoquants from Statistical Analytical Method with Results from Hydroscience Statistical Moments Method-Minneapolis

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The table shows that the Statistical Analytical (SA) method is always higher than STORM while the Statistical Moments (SM) method is almost always lower. The maximum percent control deviation between SA and STORM results is (13) to (19) while between SM and STORM it is (-10) to (-14).

DISCUSSION

From the analysis carried out in this investigation, it was found that the two statistical methods produce results with approximately the same maximum deviations from STORM results. On the average, the Statistical Moments method produced results slightly closer to STORM than did the Statistical Analytical method.

Like STORM, the Statistical Analytical method has been developed to deal with several water quantity and quality criteria such as loadings to receiving water bodies. It can deal directly with

i) average annual number of overflows (Figure 2.3);
ii) average annual volume of overflows;
iii) percent runoff control, and
iv) percent pollutant control;

and similar criteria. The SM method could be developed to deal with these factors as well.

The removal of pollutants by detention in storage has been incorporated directly in the SA method analysis, Figure 2.4. The hook-shaped isoquants result from the way in which storage of stormwater affects the quality. It has been assumed that there is a logarithmic relation between rate of suspended sediment removal and detention time (Equation 4.46). For a given storage volume the effect of increasing the treatment rate is to reduce the degree of pollution control in the storage itself. As treatment rate rises detention time decreases, and the loss of pollution control through decreased sedimentation in storage becomes more than the gain in control due to the combination of higher treatment and higher control of runoff. The extent of this effect depends on the relative effectiveness of sedimentation in the storage and treatment in the plant.

With these results in hand, it becomes clear that the optimal combination for controlling pollution to any desired level is to the left of the hook in the appropriate curve, since at that point both storage and treatment are smaller than they are to the right. This result limits the sensible range of combinations. With the sedimentation relationship used here the storage is very effective in controlling pollution, as can be seen by comparing Figures 2.1 and 2.2 with Figure 2.4.

The Statistical Analytical method also incorporates a factor to account for the operation of the storage to reduce the pollutant concentrations in overflows by making controlled releases which bypass the treatment plant when storm runoff is predicted. For the present assignment this factor was not applied.

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SUMMARY OF CONCLUSIONS

1) Since the SA and SM methods both give results with approximately the same range of discrepancy when compared to STORM, either method can be used for preliminary analysis with the same degree of confidence in the results.

2) Since the comparisons among the three methods are similar for all five cities studied, both mathematical methods account for important variations in climate.

3) The Statistical Moments method gives results which are often closer to those of STORM than results from the Statistical Analytical method.

4) The Statistical Analytical method can be implemented on programmable calculators or mini-computers and the Statistical Moments method is available as nomograms; both methods are portable and easy to use.

5) The effect of pollutant removal by detention in storage has been demonstrated for the Statistical Analytical method.

6) The Statistical Analytical method calculates with the same input, a larger number of parameters describing the control of water quantity and quality than the currently available (1978) Statistical-Moments method.

7) The SA and SM methods can be modified to account for watershed routing and dynamic storage in pipelines.

8) A statistical approach to rainfall event water losses, based on inter-event times and a rate of soil moisture deficit, has been developed. This could conveniently be incorporated into the SA method.

9) The SA method can be programmed to produce isoquants and economic trade-off among storage and treatment options can be made directly in the preliminary analyses of stormwater control options.

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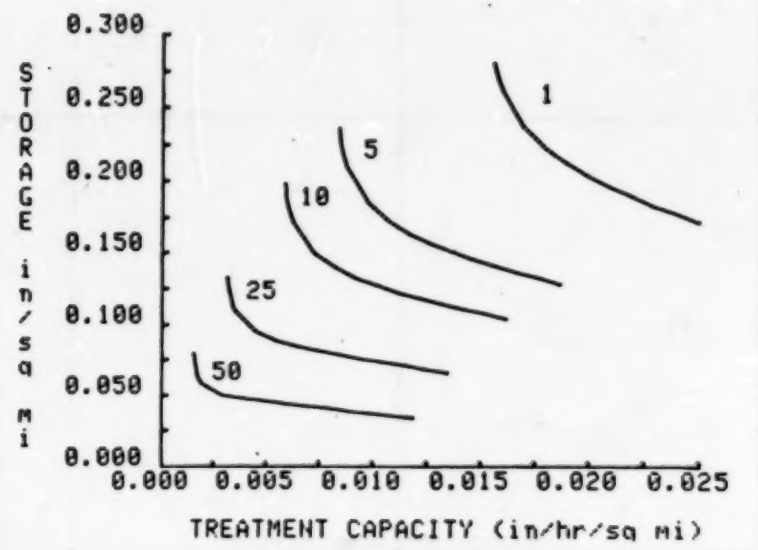

FIGURE 2.3 - Isoquants of Average Annual Number of Overflows - Minneapolis

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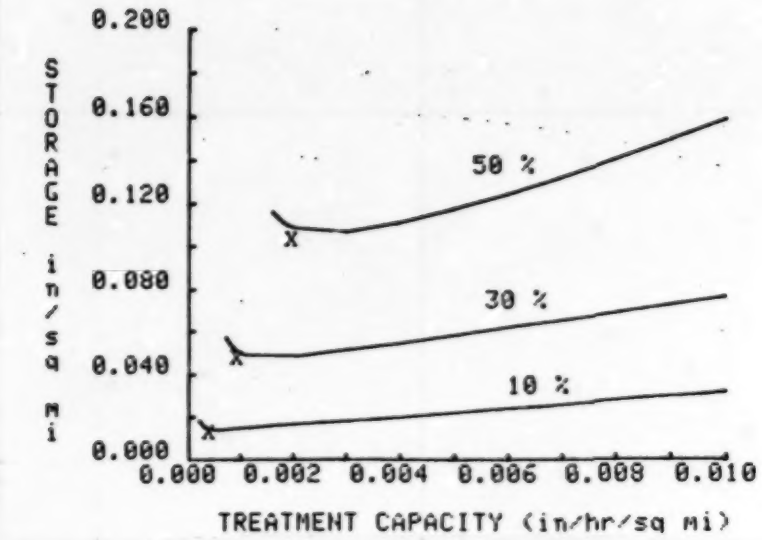

Note: Efficiency of treatment in storage, $\eta_s = 54.4*\log(RT) + 5.63$, $\eta_s < 100\%$

LEGEND

η_s is the Efficiency

RT is the Retention Time

FIGURE 2.4 - Isoquants of Suspended Solids Control - Stormwater Ponds - Minneapolis

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SECTION 3

COMPUTER SIMULATION

The computer simulation work was carried out by the team at the University of Florida, headed by J.P. Heaney and W.C. Huber, under contract to the Municipal Environmental Research Laboratory published in reports (1) and (9), which have been used here as the main source of the simulation results.

BASIC DATA FOR THE FIVE CITIES

Five cities were selected, each representing a region of the United States (1, Figure 17). For each city, twenty-five years (January, 1948 to December, 1972) of hourly precipitation data were obtained and analyzed to produce curves of the annual frequency of rainfall storm depths (1, Figure 8). Because of cost, only one year of rainfall data was used in the simulation. The "Study Year" for each city was selected such that its rainfall depth frequency curve was similar to the twenty-five year curve, (1, p. 34, 2nd and 3rd paragraphs, and Figure 9).

The following data were obtained or developed for each city (1, p. 31): total area, land use types and percentages, percent imperviousness and curb lengths, daily evaporation and street cleaning frequencies. Depression storage was assumed to be 0.01 inches (0.025 cm) for all cities. The basic hydrologic data for the five cities are given in Table 3.1.

TABLE 3.1[a] - Hydrologic Data For Study Areas

City	Study Year	Rainfall in.	Rainfall (cm)	Imperviousness 1/100	Runoff Coefficient, b_{CR}	Annual Runoff[c], AR in.	Annual Runoff[c], AR (cm)
Atlanta	1969	44.40	(113.0)	0.299	0.374	16.18	(41.10)
Denver	1960	14.98	(38.0)	0.314	0.386	5.59	(14.20)
Minneapolis	1971	29.29	(74.4)	0.293	0.370	10.50	(26.70)
San Francisco	1967	24.26	(61.6)	0.329	0.397	9.37	(23.80)
Washington, D.C.	1969	43.30	(110.0)	0.339	0.404	17.22	(43.70)

a From Ref. 1, Table 15

$b_{CR} = 0.15\ (100-I)/100 + 0.9\ I/100 = 0.15 + 0.75\ (I/100)$
where I = percent imperviousness

c From STORM analysis

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METHODOLOGY

The simulation was carried out with STORM, analyzing for each city one year of rainfall data. STORM computes the runoff from the rainfall by first subtracting the depression storage and then multiplying the effective precipitation by the runoff coefficient. Both parameters were assumed to be constant. The runoff coefficients are given in Table 3.1, and the depression storage was assumed to be 0.01 inches for all cities.

STORM neglects the transport of storm water through the basin, and the runoff hydrograph is therefore not affected by flow and/or storage in the sewerage system itself.

The watershed and facility arrangement used by STORM is shown in Figure 3.1.

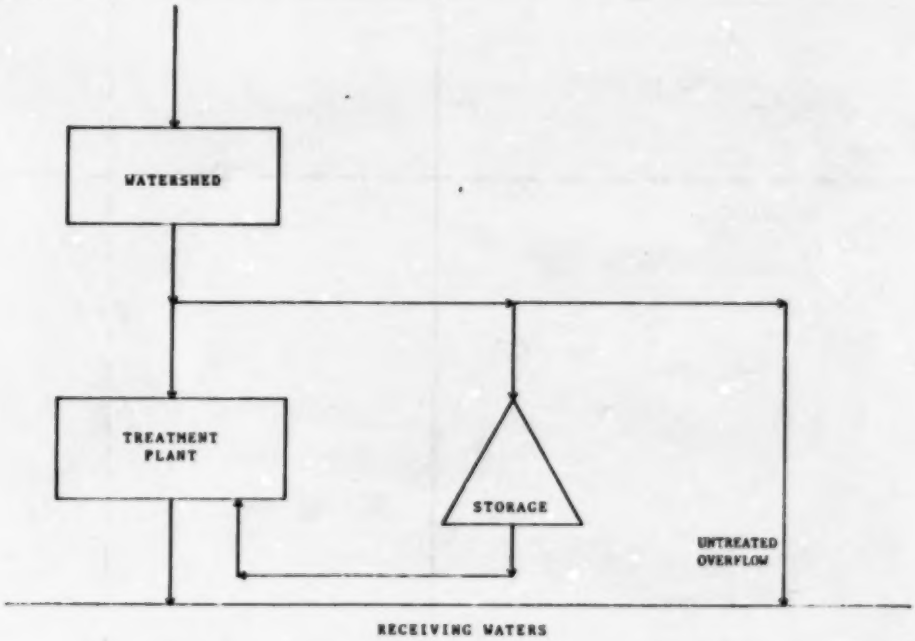

FIGURE 3.1 - Schematic Representation of the System Used in STORM

Runoff is directed to the treatment plant. When the treatment capacity is fully used, the excess runoff is directed into storage, from which it is later treated. When storage is full, the excess overflows untreated into the receiving waters.

The objective of the simulation was to generate storage/treatment isoquant (1, Figures 12 to 16) - curves giving the combinations of storage and treatment which yield a given annual pollution control. The isoquants are determined by carrying out a large number of simulations for each of the cities - each simulation computes the runoff and pollution control for the sequence of events during the study year for particular values of the storage size and the treatment capacity.

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The assumed form of the storage/treatment isoquants (1, Equation 12 and Figure 11) is

$$T = T_1 + (T_2 - T_1)e^{-kS} \qquad (3.1)$$

where

T	=	wet-weather treatment rate (inches/hour)
T_1	=	treatment rate at which the isoquant becomes parallel to the storage axis (inches/hour)
T_2	=	treatment rate at which the isoquant intersects the treatment axis (inches/hour)
S	=	storage volume (inches)
k	=	a constant (inches^{-1})

T_1 is computed from the following equation:

$$T_1 = \frac{AR}{8760} \cdot \frac{R}{100} \qquad (3.2)$$

where

AR	=	annual runoff volume (inches/year)
R	=	percent runoff control
8760	=	the number of hours in a year

T_1 is the treatment rate which would be achieved if there had been sufficient storage to have the treatment plant operate continuously. This value of T_1 may overestimate the actual amount of treatment which will be achieved with a large storage if there are times when the storage is empty and the treatment plant will therefore not be operating.

Heaney et al. then give the following explanation on how the remainder of the coefficients in Equation (3.1) are computed (1, p. 40)

> "The $T_2 - T_1$ and k terms versus R were found to be of the following general form:
>
> $$T_2 - T_1 = be^{hR}$$
>
> $$k = de^{-fR}$$
>
> Based on this analysis the following general equation for the isoquants is obtained
>
> $$T = aR + be^{hR} - (de^{-fR})S$$

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The values of the parameters a, b, h, d and f for various cities are presented in Table 16. The correlation coefficients for each fit were all above 0.99".

These fits were obtained using a number of simulation results - each giving the percent control for a specified storage-treatment combination. Some of these points are shown in the report (1, Figures 12 to 16). One of the figures is reproduced here in Figure 3.2.

The isoquant equations of Heaney and Huber do not contain all of the factors which influence the operation of storage, as discussed in the next sections, and their isoquants may not closely fit the STORM results over the complete range of storage and treatment capacities. In the economic analysis this did not pose a serious limitation because the most economical alternatives (points on the expansion path) were found to be in the central range. However, for the present assignment, in which direct comparisons are desired, the isoquants sketched by Heaney and Huber were not used - only the actual STORM results were used here in the comparisons.

The percent runoff control, R, and percent pollution control, R_1, are related through the treatment efficiency, η, by

$$R_1 = \eta R \qquad (3.3)$$

STORM can be run to use the "first flush assumption", namely: (1) the amount of pollution removal is proportional to the amount of pollution remaining, and (2) a uniform runoff of one-half inch per hour washes away 90% of the pollution in one hour (1, p. 38).

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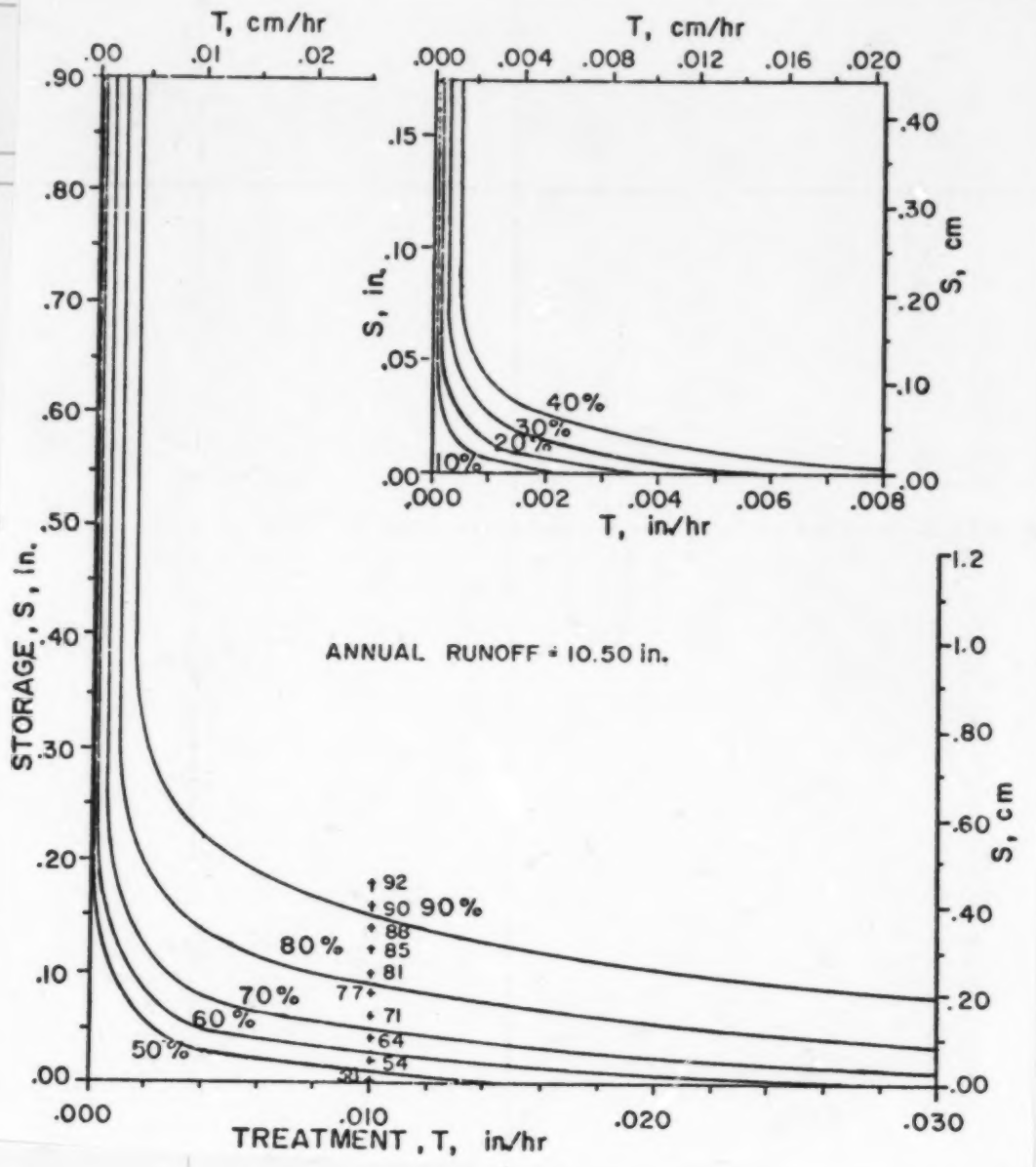

FIGURE 3.2 - Storage/Treatment Isoquants for Percent BOD Removal with First Flush - Region III - Minneapolis (Reproduced from Reference 1, Figure 14)

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SECTION 4

STATISTICAL ANALYTICAL METHOD

PURPOSE AND GENERAL APPROACH

The purpose of the analytical method is to obtain closed form expressions for the probability distributions of runoff, overflow and pollution events - expressions which reflect the natural physical processes in the watershed and the effect of man-made facilities and operations. These results can then be used in planning control strategies.

To accomplish this, the watershed has to be represented by a very simple model. Storm events are defined, and the rainfall data are analyzed to obtain the statistics of rainfall probability distributions. Using these distributions and the watershed model, probability distributions of runoff and pollution events are then derived. These distributions form the basis for determining runoff and pollution control provided by combinations of storage and treatment capacities.

The theory has been presented by Howard, with subsequent discussions and corrections (2, 3, 4). More work has been done since then (11, 12), and in the following presentation these modifications are discussed.

MODEL OF THE PHYSICAL SYSTEM

The watershed and facilities are shown schematically in Figure 4.1. This diagram may be compared to the arrangement used in STORM, as shown in Figure 3.1. Rainfall is the input to the watershed. This input is transformed into runoff, whose temporal behaviour depends on that of the rainfall and on the storage and conveyance characteristics of the watershed. The runoff picks up pollution from the watershed and flows into the man-made reservoir. Water is released from the reservoir to the treatment plant, and the treated outflow is discharged into the receiving waters. When the reservoir cannot contain all the runoff, the remainder spills into the receiving waters without going through the treatment plant. Water can also be released after detention in storage into the receiving waters without being treated. This allows the operator to prepare some empty storage when he expects the next storm, releasing into the receiving waters runoff which was already allowed to settle in the reservoir and trapping the first flush of the next storm.

The differences between this configuration of the physical system and that used in STORM are: (1) all runoff is assumed here to go through the

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storage prior to treatment, and (2) in the arrangement of Figure 4.1 it is possible to release water from the storage to the receiving waters, without going through the treatment plant but after the runoff has had some treatment in the reservoir.

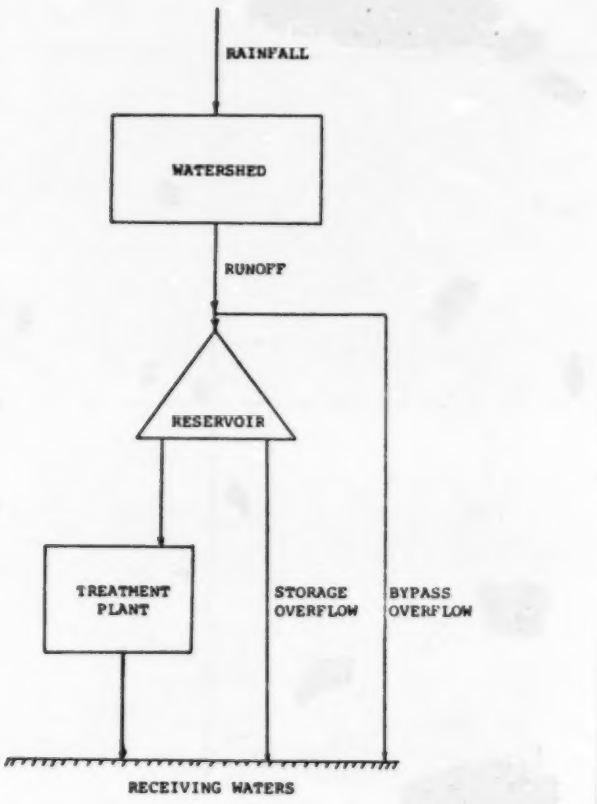

FIGURE 4.1 - Schematic Representation of the System used by the Statistical Analytical Method

The mathematical method is based on the following propositions and assumptions:

(1) Runoff is generated from the rainfall by first subtracting the depression storage, s_d, and then multiplying the remaining effective precipitation by the runoff coefficient, ϕ.

(2) The concentration of pollution in the runoff waters is constant, independent of the time between storms, rainfall intensity, or time during the storm. Any specified single pollutant (e.g. suspended solids) is being considered.

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(3) The treatment plant operates at a constant rate, Ω, as long as there is water in the reservoir. This treatment rate is assigned to storm runoff only, i.e., it is the capacity of the sewage treatment plant above that needed to treat dry weather flows as it is a separate wet-weather plant.

(4) The efficiency of the treatment plant, η_Ω, is constant.

(5) The storage reservoir has a treatment efficiency, η_s, which is due to the residence time of water in it. For an average detention time, RT, this efficiency is:

$$\eta_s = a \log (RT) + b \quad , \quad RT \geq RTMIN \qquad (4.1)$$

where (a) and (b) are empirically determined coefficients and RTMIN is some reasonable minimum residence time above which (4.1) is valid.

(6) The bypass overflow receives no treatment, and therefore enters into the receiving waters with the original pollution concentration.

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(7) Runoff enters the reservoir at a constant rate for the approximate duration of the rainfall, i.e. the temporal distribution of inflow to the reservoir is not affected by routing on the watershed or in the pipes.

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(8) The reservoir is assumed to be full at the end of the previous storm. This assumption can be replaced by others, but this has not been done here.

RAINFALL STATISTICS

Storm events are defined by specifying the minimum duration of a dry period, τ, which separates independent storms. This minimum can be selected with the aid of statistical-mathematical tools, such as the autocorrelation function of the rainfall data time series (2, p. 710). In this study we used τ=1 hour, a value which does not usually establish independence between the properties of the events so defined. However, experience showed that the loss of independence was more than equally offset by improvements to the SA results. This is because the larger values of τ necessary to define independence, at a reasonable statistical level, lead to events for which the averaging of rainfall amounts within the events is not realistic - i.e. large periods of no-rain are smudged. With a definition of independence the average number of storm events per year, ϕ, can be counted.

The duration of each storm, T_e, and its total depth are obtained directly from the hourly rainfall data. The average intensity of each storm, I_e, is its depth divided by its duration.

The duration of storm events was found to have a probability distribution which could reasonably be fitted by an exponential function

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$$f_{T_e}(t) = \lambda e^{-\lambda t} \quad , \quad t \geq 0 \qquad (4.2)$$

(See 2, 10, 12). Similarly, the average intensity of storm events was found to have a probability distribution which can be fitted by an exponential function (2, 10, 12)

$$f_{I_e}(i) = \beta e^{-\beta i} \quad , \quad i \geq 0 \qquad (4.3)$$

λ and β are the reciprocals, respectively, of the average duration, $\overline{T}_e$, and average intensity, I_e.

The volume of a storm, V_e, is the product of its average intensity and its duration

$$V_e = T_e \cdot I_e \qquad (4.4)$$

Storm duration and intensity were also found to be statistically independent (2,10,12). The probability distribution function of volumes can then be derived from those of the duration and intensity, using the relation (4.4). The mathematical procedure, explained in Ref. 2, leads to the following expression for the cumulative probability function for volumes

$$F_{V_e}(v) = 1 - \lambda\beta \int_0^\infty e^{-(y + \frac{\lambda\beta v}{y})} dy \qquad (4.5)$$

The integration was initially carried out (2) by a numerical procedure and the result given graphically (2, Figure 2). Di Toro and Small (3) give the exact solution of the integral as

$$F_{V_e}(v) = 1 - \sqrt{\lambda\beta v}\, K_1 (2\sqrt{\lambda\beta v}) \qquad v \geq 0 \qquad (4.6)$$

where K_1 is the modified Bessel function of the second kind, of order one. This function gives the probability that the storm volume, V_e, will be less than or equal to any selected value v, for all $v \geq 0$.

The probability density function for storm volumes is obtained by differentiating (4.6). This yields (3):

$$f_{V_e}(v) = 2\lambda\beta K_o (2\sqrt{\lambda\beta v}) \qquad v \geq 0 \qquad (4.7)$$

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where K_o is the modified Bessel function of the second kind of order zero.

To facilitate the remainder of the analysis it is convenient to approximate the probability density function of volumes, equation (4.7), by an exponential function:

$$f_{V_e}(v) = \zeta e^{-\zeta v} \quad , \quad v \geq 0 \qquad (4.8)$$

This approximation is satisfactory especially for large values of the volume, which are the events of greatest importance for stormwater management (12). The parameter ζ, which is the reciprocal of the average volume, $\overline{V}_e$, can be derived directly from analysis of storm volume (total depth) data, or by fitting (4.8) to (4.7).

Inter-event times, B_e, for the independent storms have also been found to be exponentially distributed (2):

$$f_{B_e}(b) = \psi e^{-\psi(b-\tau)} \quad , \quad b \geq \tau \qquad (4.9)$$

Analysis of data (2, 11, 12) has indicated that it is reasonable to take volume and inter-event times as being statistically independent.

Table 4.1 shows the rainfall parameters used for the five cities studied here.

TABLE 4.1 - Rainfall Parameters for Event Definition of 1 Hour

City	λ 1/hours	β hours/inch	ζ 1/inches	ψ 1/hours	θ events per year
San Francisco	0.329	25.30	5.00	0.018	138
Denver	0.240	31.30	6.66	0.011	98
Washington, D.C.	0.299	13.51	3.70	0.0194	158
Atlanta	0.319	14.72	3.84	0.0210	170
Minneapolis	0.344	20.79	7.14	0.0255	206

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RUNOFF STATISTICS

It is assumed that a hypothetical depression storage has to be filled before any runoff can be generated. The depression storage could be defined as a function of imperviousness (1, page 13) or as a function of the rainfall properties, such as the statistics of inter-event time. However, the STORM runs used for the present comparisons all used a value of 0.01 for depression storage (1, Table 14, Page 32) and, for consistency in the comparisons, that value was used here for all of the five cities.

When a storm volume exceeds the depression storage, s_d, the surplus precipitation is assumed to be converted into runoff through multiplication by a runoff coefficient ϕ, which accounts for losses during the storm by infiltration and evaporation. The runoff coefficient was assumed to be a function of the imperviousness, I, given by:

$$\phi = 0.15 + 0.75(I/100) \tag{4.10}$$

The average annual number of runoff events, n_r, is computed by multiplying the average annual number of storm events, θ, by the probability that a storm volume will exceed s_d:

$$n_r = \theta \text{ Prob}\left[V_e \geq s_d\right] = \theta e^{-\zeta s_d} \tag{4.11}$$

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The original theory, on which the present analysis is based, computes the average annual volume of the net precipitation, $\overline{P}'$, as follows:

$$\overline{P}' = P - \left[(\theta - n_r)\,\overline{V}_1 + n_r s_d\right] \tag{4.12}$$

where $\overline{V}_1$ is given by

$$\overline{V}_1 = \frac{1}{\zeta}\left[\frac{1 - e^{-\zeta s_d}(1 + \zeta s_d)}{1 - e^{-\zeta s_d}}\right] \tag{4.13}$$

$\overline{V}_1$ is the average volume of storms having volumes less than s_d.

The average annual net precipitation volume is next multiplied by the runoff coefficient to obtain the average annual runoff volume:

$$\overline{R} = \phi\overline{P}' \tag{4.14}$$

The probability distribution function of runoff volumes, V_r, is derived from the pdf of storm volumes, resulting in:

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$$f_{V_r}(v) = \begin{cases} 1 - e^{-\zeta s_d} & , \quad v = 0 \\ \zeta e^{-\zeta (s_d + v)} & , \quad v \geq 0 \end{cases} \tag{4.15}$$

For small values of s_d, $f_{V_r}(0) \simeq 0$, and the pdf of runoff volumes can be approximated as

$$f_{V_r}(v) = \zeta' e^{-\zeta' v} \quad , \quad v \geq 0 \tag{4.16}$$

with

$$\zeta' = \frac{1}{\bar{V}_r} = \frac{n_r}{\bar{R}} \tag{4.17}$$

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The distribution of runoff event durations, T_r, will be somewhat modified from the distribution of storm durations, due to the removal of the low volume events and the truncating effect of the depression storage.† Since the durations and volumes of storms are only weakly dependant (12), the distribution of runoff durations will be also exponential.

$$f_{T_r}(t) = \lambda' e^{-\lambda' t} \quad , \quad t \geq 0 \tag{4.18}$$

with parameter λ' given by

$$\lambda' = \frac{\lambda}{1 - \lambda t'} \tag{4.19}$$

t' is the amount by which the average runoff duration is shorter than the average storm duration, and is assumed herein to be:

$$t' = 1 \text{ hour} \tag{4.20}$$

If s_d is sufficiently small, and the number of storm events which fail to produce runoff is consequently not large, runoff inter-event times, B_r, will also be exponentially distributed:

$$f_{B_r}(b) = \psi' e^{-\psi'(b - \tau)} \quad , \quad b \geq \tau \tag{4.21}$$

† In practice, since the depression storage is usually assumed to be 0.01 inches and this corresponds to the minimum rainfall which is measured, the first term in brackets in (4.12) is found by counting the number of events recorded as having 0.01 inches of rainfall.

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The parameter ψ', which is the reciprocal of the average inter-event times for runoff events, is obtained by the following consideration. The total number of hours in the rainy season, H, is computed from

$$H = \theta \cdot \bar{T}_e + (\theta - 1)\bar{B}_e = \frac{\theta}{\lambda} + \frac{\theta - 1}{\psi} \qquad (4.22)$$

The first term accounts for θ storm events of average duration $\bar{T}_e = 1/\lambda$, and the second term for $(\theta - 1)$ inter-events of average length $\bar{B}_e = 1/\psi$. The same length of the rainy season can be expressed in terms of the runoff event durations and inter-event times.

$$H = n_r \cdot \bar{T}_r + (n_r - 1)\bar{B}_r = \frac{n_r}{\lambda'} + \frac{n_r - 1}{\psi'} \qquad (4.23)$$

from which

$$\psi' = \frac{\lambda'(n_r - 1)}{H\lambda' - n_r} \qquad (4.24)$$

Since runoff volume and duration are exponentially distributed, and are independent, the runoff intensity

$$I_r = \frac{V_r}{T_r} \qquad (4.25)$$

is also (approximately) exponentially distributed

$$f_{I_r}(i) = \beta' e^{-\beta' i} \quad , \quad i \geq 0 \qquad (4.26)$$

with

$$\beta' = \frac{\zeta'}{\lambda'} \qquad (4.27)$$

We have therefore concluded that, subject to the assumptions and approximations made, runoff event intensities, durations, volumes and inter-event times are all exponentially distributed with parameters which can be derived from those of the rainfall parameters.

For the analysis carried out in this study, the dynamic storage and conveyance effects of the sewerage system on the runoff are ignored. Thus, the outflow from the watershed - which is the inflow to the storage reservoir - is assumed to appear as rectangular hydrographs of intensity I_r and duration T_r, arriving at inter-event times B_r.

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OVERFLOW STATISTICS

The runoff from the watershed appears as the inflow to the reservoir. The original theory assumed treatment during all storms at plant capacity for the average storm duration (2, eqn. 44). This assumption has subsequently been partially removed, as will be discussed below, and the present analysis used this updated method.

Runoff events whose average intensity, I_r, is less than or equal to the treatment rate, Ω, will not cause overflows since the storage is being drawn down by the treatment plant more rapidly than it is being filled by the runoff. Such events do not utilize the storage range.

Since the treatment plant is assumed to operate continuously (as long as there is water in the reservoir), then for runoff with larger intensities, ($I_r > \Omega$), only the excess intensity, ($I_r - \Omega$) will utilize a portion of the range of storage available in the reservoir. The expected value of treatment rate during storms (7) is

$$\bar{I}_\Omega = \bar{I}_1 + \Omega e^{-\beta'\Omega} \tag{4.28}$$

where

$$\bar{I}_1 = \frac{1}{\beta'}\left\{\frac{1 - e^{-\beta'\Omega}(1 + \beta'\Omega)}{1 - e^{-\beta'\Omega}}\right\} \tag{4.29}$$

is the average intensity for events with intensities less than the treatment rate, Ω. The pdf of the storage-utilizing runoff intensities,

$$I_s = \begin{cases} 0 & , \ I_r \leq \Omega \\ I_r - \Omega & , \ I_r > \Omega \end{cases} \tag{4.30}$$

is

$$f_{I_s}(i) = \begin{cases} 1 - e^{-\beta'\Omega} & , \ i = 0 \\ \beta' e^{-\beta'(\Omega + i)} & , \ i > 0 \end{cases} \tag{4.31}$$

For small values of Ω, $f_{I_s}(i) \simeq 0$ and this pdf can be approximated by

$$f_{I_s}(i) = \beta'' e^{-\beta'' i} \quad , \ i \geq 0 \tag{4.32}$$

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The expected value of the annual runoff volume which will be processed by the treatment plant during storms is

$$\overline{V}_\Omega = \overline{I}_\Omega \cdot \overline{T}_r = \overline{I}_\Omega/\lambda' \tag{4.33}$$

The remainder of the runoff volume will utilize storage or overflow. Its average annual value is (7),

$$\overline{V}_s = \overline{V}_r - \overline{V}_\Omega = \frac{1}{\zeta'} - \frac{\overline{I}_\Omega}{\lambda'} \tag{4.34}$$

Denoting $\zeta'' = 1/\overline{V}_s$ we obtain

$$\zeta'' = \frac{\lambda'\zeta'}{\lambda' - \overline{I}_\Omega\zeta'} \tag{4.35}$$

and we again accept the approximation

$$f_{V_s}(v) = \zeta''e^{-\zeta''v} \quad , \quad v \geq 0 \tag{4.36}$$

The average annual number of events which utilize storage is

$$n_s = n_r \cdot \text{Prob}\{I_r > \Omega\} = n_r e^{-\beta'\Omega} \tag{4.37}$$

The reciprocal of the average inter-event time, $\overline{B}_s$, for storage-utilizing events is given by

$$\psi'' = \frac{\lambda'(n_s - 1)}{H\lambda' - n_s} \tag{4.38}$$

(see Equation (4.24) and the explanation leading to it). The pdf of inter-event times for these events can be approximated by

$$f_{B_s}(b) = \psi''e^{-\psi''(b - \tau)} \quad , \quad b \geq \tau \tag{4.39}$$

The theory assumed that the reservoir was full at the end of the previous storm. Under this assumption, the empty storage space in the reservoir when runoff arrives depends on the rate at which the reservoir is being emptied through the treatment plant, Ω, and the time which has elapsed since the last storm.

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For a reservoir of total capacity S the amount of overflow can be determined from Figure 4.2.

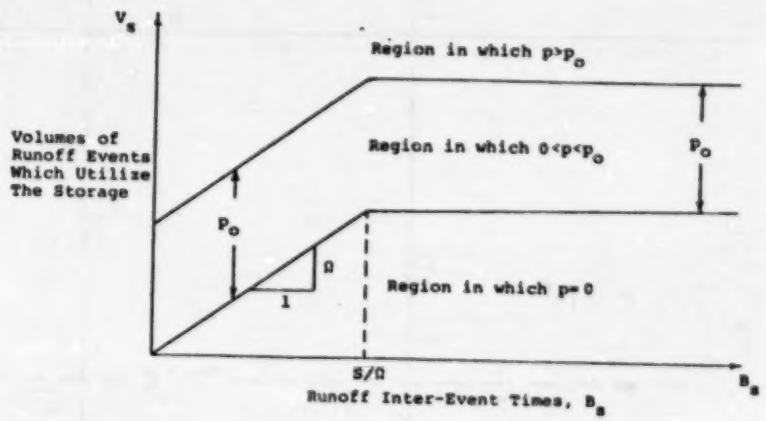

FIGURE 4.2 - Definition Sketch For Overflows

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The probability of having an overflow greater than p_o is

$$G_p(p_o) = \text{Prob}\left[p \geq p_o\right] = \iint_{(A)} f_{V_s}(v)\, f_{B_s}(b)\, dvdb \qquad (4.40)$$

where A is the region above the upper line in Figure 4.2. The pdf's of V_s and B_s are given in Equations (4.36) and (4.39), respectively. The integration yields

$$G_p(p_o) = e^{-\zeta'' p_o}\left\{\frac{\psi'' e^{-\psi''\tau} + \zeta''\Omega\ \text{EXP}\left[-\{\psi''(\frac{S}{\Omega} - \tau) + \zeta'' S\}\right]}{\psi'' + \zeta''\Omega}\right\} \qquad (4.41)$$

which can also be written as follows

$$G_p(p_o) = e^{-\zeta'' p_o} G_p(0) \qquad (4.42)$$

$$= e^{-\zeta'' p_o}\{1 - \text{Prob}(p = 0)\}$$

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where $G_p(0)$ = probability of having any overflow greater than zero = the term in brackets in Equation (4.41).

This last result differs in two ways from the original result by Howard (2, Equation 23): (1) it is adjusted for the minimum lag time, τ, and (2) an unrealistic boundary condition has been revised here.

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The expected number of overflow events is given by

$$n_o = n_s \text{ Prob } (p > 0) = n_s G_p(0) \tag{4.43}$$

The average annual volume of overflows is

$$P_u = \frac{n_o}{\zeta''} = \frac{n_s G_p(0)}{\zeta''} \tag{4.44}$$

The average annual percent runoff control is

$$C_R = 100 \left(1 - \frac{P_u}{R}\right) \tag{4.45}$$

6-1/2

POLLUTION CONTROL

We assume that there is some treatment in the storage, mostly due to settling. Thus, the efficiency of treatment in storage, η_s, is primarily a function of the residence time. The assumed efficiency function is given in Equation (4.1) which is based on the form given in ASCE sedimentation manual (13) and some preliminary data from ponds in Winnipeg (14). Reliable data on treatment in storage are not currently available. From actual data from detention ponds in Winnipeg, Canada, the coefficients in Equation (4.1) were estimated, leading to

$$\eta_s = 54.4 \log (RT) + 5.63, \text{ for } \eta_s < 100\% \text{ and } RT > RTMIN \tag{4.46}$$

RT is the residence time, and the value

$$RT = \frac{S}{2\Omega} \tag{4.47}$$

was used. This corresponds to the time necessary to treat half the storage volume.

When runoff occurs water is routed through the storage, to utilize the treatment of the storage facility. The water is then released through the treatment plant, which now operates at an efficiency η_Ω. η_Ω is assumed to be independent of η_s. The overall efficiency of this system is then

$$\eta = \eta_s + \eta_\Omega - \eta_s \eta_\Omega \tag{4.48}$$

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When storage is full and the treatment plant is operating at capacity, there is overflow from storage. This overflow has gone through the reservoir, and has therefore had some treatment (in storage). This treatment is probably less then η_s, and is assumed to be

$$T\,\eta_s \quad \text{with} \quad 0 \leq T \leq 1 \tag{4.49}$$

For the present study T = 0 was assumed. This is conservative and is equivalent to assuming that overflows completely bypass the reservoir and enter the receiving waters with their original concentration.

The percent pollution control is

$$C_p = \frac{100\ (R - P_u)\ \eta_\Omega + P_u\ T\ \eta_s}{R} \tag{4.50}$$

Treatment efficiencies were assumed to be independent of design capacity or operating conditions, as shown below:

Separate Sewerage

Ponds: $\eta_s = 54.4 \log (S/2\Omega) + 5.63$, $\eta_s \leq 100$, $S/2\Omega >$ RTMIN.

Primary: $\eta_\Omega = 60\%$

Swirl Concentrator: $\eta_\Omega = 20\%$

Physical - Chemical: $\eta_\Omega = 90\%$

Combined Sewerage

Activated sludge with sedimentation tanks upstream: η_Ω= 75% + tank efficiency

Complete secondary: $\eta_\Omega = 93\%$

Swirl Concentrator: $\eta_\Omega = 40\%$

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FURTHER REFINEMENTS OF THE METHOD

The previous sections present the statistical analytical method as used in this study. Further potential refinements, which have not yet been tested, are presented below.

Rainfall Losses

In the method presented above, the volume of each rainfall event is reduced by a constant depression storage runoff and coefficient. The following theory presents these losses in terms of a rate of moisture deficit on the watershed which is a function of the time since the last storm.

Assuming that the moisture deficit at the end of a storm is zero, and that its rate of increase, m, is a constant, the total runoff volume, R, resulting from a storm of volume V, is given by either:

$$R_1 = V - mB \text{ for } B \leq \frac{m_x}{m} \tag{4.51}$$

or

$$R_2 = V - m_x \text{ for } B \geq \frac{m_x}{m} \tag{4.52}$$

where m_x is the maximum possible moisture deficit. The probability density function for storm runoff volume may now be derived from the distribution of rainfall inter-event times, $f_B(b)$, and the distribution of rainfall depths, $f_V(v)$ which have been presented above. The development of this function is exactly analogous to the development of the theory of storage and treatment plant overflows and yields the probability of having a runoff volume greater than γ_o, (see Equation (4.41)):

$$G_R(R_o) = e^{-\zeta'' m_o}\left[\frac{\psi'' e^{-\psi''\tau} + \zeta'' m \text{EXP} - \{\psi''(\frac{m_x}{m} - \tau) + \zeta'' m_x\}}{\psi'' + \zeta'' m}\right] \tag{4.53}$$

The selection of the rate of moisture deficit increase, m, and the maximum moisture deficit, m_x, can be made from field data on soil moisture and soil structure. Where these data are not available, the following considerations can be used.

Under some conditions, the average rate of soil moisture deficit increase will be approximately equal to the average rate of actual evapotranspiration, e

$$m \simeq e \tag{4.54}$$

From (4.53) the average annual number of runoff events, n_r, is given by

$$n_r = \theta \cdot \text{Prob}\,(r > 0) = \theta \cdot G_R(0) \tag{4.55}$$

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and the average annual volume of runoff, $\bar{R}$, by:

$$\bar{R} = \frac{n_r}{\zeta} = \frac{\theta G_R(0)}{\zeta} \tag{4.56}$$

Where estimates of the runoff are available Equation (4.56) may be solved numerically or by trial and error for the moisture deficit parameters.

The probability function of Equation (4.53) is not suitable for use in further development of the overflow theory because of its complexity. However, the values of n_r and R may be used in Equation (4.17) and the subsequent procedures followed as before.

Watershed Routing and Dynamic Storage in Pipelines

The effect of watershed routing and dynamic storage in pipelines on the rainfall hyetograph is to produce a runoff hydrograph. In the method presented above, the rectangular hyetograph is modified only by the losses and remains a rectangular runoff hydrograph. The following procedure will permit consideration of the transformation in shape from the rainfall hyetograph to runoff hydrograph.

For simplicity, consider the rainfall hyetograph and triangular hydrograph shape of Figure 4.3. The effect of watershed routing, including dynamic pipeline storage, is to lengthen the runoff duration, t_q, and possibly to modify the peak intensity of runoff, i_q. Working with unit areas, and defining t_r and i_r to be the net (after losses are taken into account) rainfall duration and intensity respectively, the volume of the two shapes must be equal:

$$\frac{1}{2} i_q t_q = i_r t_r \tag{4.57}$$

If the catchment is small (time to peak discharge ≃ 1 hr) and there is little storage in the pipelines, steady flow will be reached quickly and the peak runoff will be a linear function of the net intensity and the area of the catchment (a unit area in this case):

$$i_q = i_r \tag{4.58}$$

The duration of runoff, t_q, is then:

$$t_q = 2t_r \tag{4.59}$$

Since the peak flow, i_q, can only be less than or equal to i_r, this is a limiting case.

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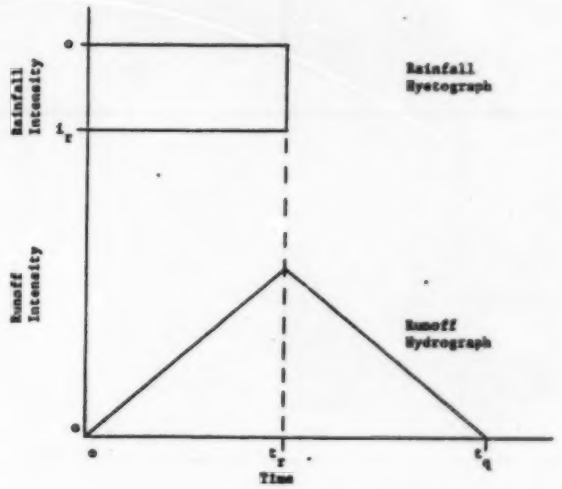

FIGURE 4.3 - Rainfall Hyetograph And Runoff Hydrograph

For large catchments with significant pipeline storage the peak flow will be less than the net intensity,

$$i_q < i_r \tag{4.60}$$

and

$$t_q > 2t_r \tag{4.61}$$

In this case, some estimate of either the average ratio of peak flow to net intensity or time of runoff to net rainfall duration is required.

In reality the shape of the hydrograph depends on both the duration and the intensity of the rainfall; higher intensity events cause the hydrograph to peak more quickly than lower intensity events and the duration of the recession depends on the peak flow. This phenomenon is too complex to consider here so a more simplified approach will be taken. For urban stormwater watersheds, a typical value of the ratio of the duration of runoff which causes overflows to rainfall duration might be 3,

$$t_q = 3t_r \tag{4.62}$$

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although on large watersheds and for substantial volumes of pipeline storage, the ratio might be greater. From the geometry of the hydrograph, the peak flow for Equation (4.62) is given by:

$$i_q = \frac{2}{3} i_r \tag{4.63}$$

Equation (4.62) and (4.63) have the general form:

$$t_q = ct_r \tag{4.64}$$

and

$$i_q = \frac{2}{c} i_r \tag{4.65}$$

where c is a coefficient of dynamic storage available in the pipelines determined for the size of the watershed and volume (it probably often falls in the range from 2 to 10). The distribution of runoff durations, T_q, can now be approximated as:

$$f_{T_q}(t) = \lambda' e^{-\lambda' t} \qquad t \geq 0 \tag{4.66}$$

with

$$\lambda' = \lambda / c \tag{4.67}$$

A first estimate of λ' is given by Equation (4.19).

The peak runoff intensity for a triangular hydrograph of volume V_q and duration T_q is:

$$I_q = \frac{2V_q}{T_q} \tag{4.68}$$

If all the losses are accounted for in the moisture deficit procedure outlined above, and it is assumed that there are no additional losses during the flow through the pipelines, then the probability density function of hydrograph volumes is exponential, with the same parameter, ζ', as for net storm volumes (Equation 4.18). The probability density function of the hydrograph peak intensity, I_q, is then:

$$f_{I_q}(i) = \frac{2\zeta'\lambda'}{(2\lambda' + \zeta' i)^2} \tag{4.69}$$

The expected value of the treatment rate during storms, Equation (4.28), must now be modified to account for the geometry of the hydrograph. Storms with peak intensities less than or equal to the treatment rate can be fully

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processed during the event, and for these events the expected rate of treatment will be one half of the expected rate of peak flow.

For peak flows greater than the treatment rate only a portion of the storm can be treated. From the geometry of the hydrograph, if the peak flow rate is very large compared to the treatment rate, the expected rate of treatment during the storm will approach the treatment rate. If the peak flow rate is relatively small, the expected rate of treatment will approach one half the treatment rate. The average rate of treatment, $\bar{I}_2$, during events having peak intensities greater than the treatment rate is given by:

$$\bar{I}_2 = K\Omega \tag{4.70}$$

with K approximated by:

$$K = 0.5 + 0.5/(10 - \beta'\Omega) \qquad \beta'\Omega < 9 \tag{4.71}$$

and

$$K = 1.0 \qquad \beta'\Omega \geq 9 \tag{4.72}$$

where a relatively large intensity is defined as one order of magnitude (10) larger than the average intensity. The average treatment rate during all events, from Equation (4.28) becomes:

$$\bar{I}_\Omega = .5\bar{I}_1 + K\Omega e^{-\beta'\Omega} \tag{4.73}$$

The remainder of the theory as presented earlier in this section may now be followed as before.

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SECTION 5

STATISTICAL MOMENTS METHOD

INTRODUCTION

We gave the method developed by Hydroscience (5,8) the name statistical moments (SM) method merely for ease of identification. Both it and the method presented in the previous chapter deal explicitly with the statistical characterization of runoff, overflow and pollution events. The SA method results in a functional expression for the probabilities; the SM method uses the first two statistical moments (mean and standard deviation) of the rainfall data in generating the desired probabilities.

The two methods differ in many aspects, as will become evident from comparing the following presentation with that of the previous section. The method is described in detail elsewhere (5,15).

METHODOLOGY

The following is a condensed presentation of the method, as explained in (5), pp. 3-43 to 3-65.

Hourly rainfall data, for at least five years, are analyzed. Storms are defined by a period of τ hours without rain (τ=3 hours is recommended). For each storm, four variables are defined:

- v = unit volume (inches)
- d = duration (hours)
- i = average intensity = v/d (inches/hour)
- δ = time since previous storm (hours), measured between mid-points of the successive storms.

A critical period for analysis is selected (e.g. the summer months). Using the data for this period for all years of record, the mean and coefficient of variation (= standard deviation/mean) for all four variables are computed. They are:

Variable	Mean	Coefficient of Variation
Volume	$\bar{V}$	ν_v
Duration	$\bar{D}$	ν_d

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Variable	Mean	Coefficient of Variation
Intensity	I	ν_i
Time between storms	Δ	ν_δ

v, d and i have been found to follow a gamma distribution. The runoff volume per storm, $V_R = 3630 \cdot C_v \cdot v \cdot A$, has a mean

$$V_R(ft^3) = 3630 \cdot C_v \cdot V(inches) \cdot A(acres) \qquad (5.1)$$

where A is the drainage area, and C_v the runoff coefficient. The flow rate of a storm, $q = C_v \cdot i \cdot A$, has a mean

$$Q_R(cfs) = C_v \cdot I(inches/hour) \cdot A(acres) \qquad (5.2)$$

The following relationships between the coefficients of variation of the runoff and rainfall are assumed:

$$\nu_{v_R} = \nu_v \qquad (5.3)$$

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and

$$\nu_q = \nu_i \qquad (5.4)$$

The mean stormwater loading rate during a storm is defined by

$$W_R(lbs/day) = 5.4 \cdot \bar{c}\ (mg/l) \cdot Q_R(cfs) \qquad (5.5)$$

where $\bar{c}$ is the average concentration of pollution in the runoff. A correction factor can be introduced into Equation (5.5) if there is evidence that the concentration and flow are correlated.

If q and c are assumed independent, the variation of W_R is given by

$$\nu_w = \nu_q \cdot \nu_c \cdot \sqrt{1 + 1/\nu_q^2 + 1/\nu_c^2} \qquad (5.6)$$

The storm loading rate is a product of two random variables - runoff flow and concentration - which are gamma distributed. As a first estimate, the storm loading rate is also gamma distributed, with the mean W_R and coefficient of variation ν_w given above. One can, therefore, compute probabilities of a storm having a loading rate in any specified interval of values. A long term average mass discharge rate is defined by

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$$W_o = W_R \cdot D/\Delta \qquad (5.7)$$

W_R would be the storm loading intensity on the receiving water in the absence of any facilities. An existing or proposed system for handling stormwater is characterized by an excess capacity Q_I in the sewer system and an excess in system storage V_E. These are the excess capacities over what is needed to handle the dry-weather flow.

The effect of these devices on the fraction of the total pollution load which will be captured is computed (details are given in Ref. 8) and plotted. The following plots are provided:

(a) $f_I = \frac{\overline{W}}{W_R}$ = fraction of load not captured vs $\frac{Q_I}{Q_R}$ for different values of ν_q.

(b) $f_v = \frac{\overline{W}}{W_R}$ = fraction of load not captured vs $\frac{V_E}{V_R}$ for different values of ν_{v_R}.

A correction to f_I can be applied to account for the first flush effect.

The fraction of the load not captured by a combination of Q_I and V_E is

$$f_{IV} = f_I f_V \qquad (5.8)$$

If it is further assumed that the load captured by the conveyance system receives treatment with a fractional removal r, then the resultant mean loading rate is

$$W_R^* = f_{IV} W_r + (1 - f_{IV}) W_R (1 - r) \qquad (5.9)$$

COMMENT ON THE METHODOLOGY

The SM method has the advantage of using two parameter distributions for the density functions and it should therefore be capable of a good representation of the actual rainfall distributions. The SA method uses a distribution for which the mean and the standard deviation are the same.

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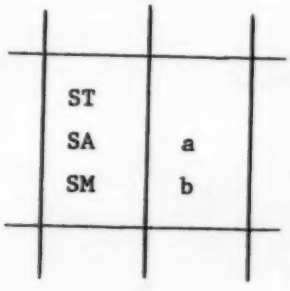
SECTION 6

COMPILATION OF RESULTS

Results from the computer simulation program "STORM" were first compiled to determine the combinations of storage (S) and treatment (T) for which results from the Statistical Analytical and Statistical Moments methods would be required. To provide a valid comparison both methods were applied using the rainfall statistics of the data used by STORM. In addition, rainfall losses were identical in both methods. Since the Statistical Moments method does not use a depression storage, a value of 0.01 inches, used in STORM and the Statistical Analytical method, was subtracted from the rainfall record before the required statistics were obtained. In applying the Statistical Moments method some judgement was required in reading the graphs required for a solution and it is therefore possible that slightly different results could be obtained by other users.

READING THE SUMMARY TABLES

(1) For each combination of S and T there are five values in a box:



ST = % control from STORM
SA = % control from S-A method (Howard)
SM = % control from S-M method (Hydroscience)

$$a = \frac{SA - ST}{ST} \times 100 = \%\ \text{deviation of SA from ST}$$

$$b = \frac{SM - ST}{ST} \times 100 = \%\ \text{deviation of SM from ST}$$

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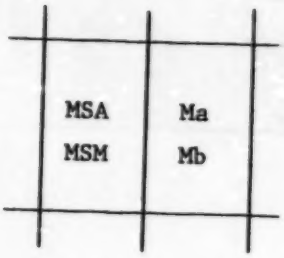
(2) The column and row labeled MAX DEV give the maximum deviations:



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MSA = maximum deviation of SA from ST, for the line or column
MSM = maximum deviation of SM from ST, for the line or column
Ma = maximum value of a, for the line or column
Mb = maximum value of b, for the line or column

Note: MSA and Ma may result from different S/T combinations. MSA is the difference in % control, Ma is a % deviation of SA from ST. The same applies for SM.

(3) The lower right-hand box gives the maximum values over all combinations of S and T for the city.

Example: for Washington

Max(MSA) = 15 Maximum deviation of SA(Howard) from STORM
Max(MSM) = -11 Maximum deviation of SM(Hydroscience) from STORM
Max(Ma) = 36 Maximum percent deviation of SA(Howard) from STORM
Max(Mb) = -73 Maximum percent deviation of SM(Hydroscience) from STORM

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TABLE 6.1

Comparison of Percent Runoff Control Results for Atlanta, Georgia

T, Treatment, Inches/Hour

LEGEND

Results of % Runoff Control	% Deviation from STORM
STORM	--
Statistical-Analytical	SA
Statistical-Moments	SM

S, Storage in Inches	.001		.002		.004		.006		.008		Max Dev.	
.000	3 4 1	33 -67	6 8 4	33 -33	12 15 7	25 -42	17 22 13	29 -24	21 28 13	33 -38	7 -8	33 -67
.005	6 7 1	17 -83	10 11 5	10 -50							1 -5	17 -83
.010	9 10 2	11 -78	12 14 5	17 -58							2 -7	17 -78
.015	11 13 3	18 -73	14 17 6	21 -57							3 -8	21 -73
.020	13 16 3	23 -77	16 20 8	20 -50							4 -10	23 -77
.025	14 18 6	29 -57	18 23 15	28 -17							5 -8	29 -57
.030	16 20 10	25 -38	20 25 16	25 -20							5 -6	25 -38
.035	17 22 11	29 -35	22 28 17	27 -23							6 -6	29 -35
.040	19 24 12	26 -37	23 30 20	30 -13	29 38 20	31 -31					9 -9	31 -37
.050	21 26 22	24 5	26 34 28	31 8							8 2	31 8
.060			29 37 32	28 10	35 46 34	31 -3					11 3	31 10
.070			31 40 33	29 6							9 2	29 6
.080			33 42 35	27 6	40 52 37	30 -8					12 -3	30 -8
.090			36 44 37	22 3							8 1	22 3
.100			38 46 41	21 8	44 57 43	30 -2					13 3	30 8
.120					48 61 47	27 -2					13 -1	27 -2
.140					51 64 56	25 10					13 5	25 10
.160					55 67 59	22 7					12 4	22 7
.180					58 68 61	15 5					10 1	15 5
.200					61 70 63	15 3					9 2	15 3
MAX DEV	5 -10	33 -83	9 -5	33 -58	13 5	31 -31	5 -4	29 -24	7 -8	33 -38	13 -10	33 -83

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Results of % Runoff Control	% Deviation from STORM
STORM	--
Statistical-Analytical	SA
Statistical-Moments	SM

TABLE 6.2

Comparison of Percent Runoff Control Results for Denver, Colorado

T, Treatment, Inches/Hour

S, Storage in Inches

	.001		.002		.004		.006		.008		.010		Max Dev.	
.000	7 10 1	43 -86	14 19 6	36 -57	27 34 17	26 -37	36 46 28	28 -22	45 56 35	24 -22	51 65 41	27 -20	14 -10	36 -86
.005	13 15 2	15 -85	20 24 8	20 -60									4 -12	20 -85
.010	17 21 5	24 -71	23 29 13	26 -43							58 72 44	24 -24	14 -14	26 -71
.015	20 26 8	30 -60	27 34 18	26 -33									7 -12	30 -60
.020	23 30 12	30 -48	30 38 16	27 -47							63 78 49	24 -22	15 -14	30 -48
.025	26 34 18	31 -31	32 42 24	31 -25									10 -8	31 -31
.030	28 37 25	32 -11	35 46 32	31 -9							67 83 55	24 -18	16 12	32 -18
.035	30 40 26	33 -13	37 49 32	32 -14									12 -5	33 -18
.040	31 43 30	39 -3	40 53 35	33 -13	50 65 36	30 -28					70 86 59	23 -16	16 -14	39 -28
.050	35 48 33	37 -6	43 58 39	35 -9									13 -4	37 -9
.060			47 62 40	32 -15	58 74 49	24 -16					76 91 64	20 -16	16 -12	32 -16
.070			50 66 47	32 -6									16 -3	32 -6
.080			53 69 54	30 2	64 80 60	25 -6					80 95 71	19 -11	16 -9	30 -11
.090			56 72 57	29 2									16 1	29 2
.100			59 74 62	25 6	69 85 65	23 -6					84 96 75	14 -11	16 -9	25 -11
.120					73 87 65	19 -11					87 98 78	13 -10	14 -9	19 -11
.140					77 90 66	17 -14					89 98 83	10 -7	13 -11	17 -14
.160					80 91 66	14 -18					92 99 84	8 -9	11 -14	14 -18
.180					83 92 67	11 -19					94 99 87	5 -7	9 -16	11 -19
MAX DEV	13 -12	43 -86	16 -14	36 -60	16 -14	30 -37	10 8	28 -22	11 -10	24 -22	16 -14	27 -20	16 -14	43 -86

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Results of % Runoff Control	% Deviation from STORM
STORM	--
Statistical-Analytical	SA
Statistical-Moments	SM

TABLE 6.3

Comparison of Percent Runoff Control Results for Minneapolis, Minnesota

T, Treatment, Inches/Hour

S, Storage in Inches

	.001		.002		.004		.006		.008		.010		Max Dev.	
.000	6 8 1	33 -83	11 15 4	36 -64	21 27 9	29 -57							6 -12	36 -83
.005	12 n 14 6	17 -50	18 21 6	17 -67									3 -12	17 -67
.010	16 20 9	25 -44	22 27 10	23 -55									5 -12	25 -55
.015	19 25 12	32 -37	26 33 15	27 -42									7 -11	32 -42
.020	22 30 20	36 -9	29 38 23	31 -21									9 -6	36 -21
.025	25 33 26	32 4	31 42 28	35 -10									11 -3	35 -10
.030	27 36 29	33 7	34 46 31	35 -9									12 -3	35 -9
.035	29 39 32	34 10	36 49 34	36 -6									13 3	36 10
.040	31 41 33	32 6	38 52 37	37 -3	47 64 40	36 -15							17 -7	36 -15
.050	35 44 38	26 9	42 57 41	36 -2									15 3	36 9
.060			46 60 50	30 9	54 73 50	35 -7							19 4	35 9
.070			49 63 53	29 8									14 4	29 8
.080			52 65 59	25 13	60 78 61	30 2							18 7	30 13
.090			55 66 62	20 13									11 7	20 13
.100			58 67 63	16 9	65 82 65	26 0							17 5	26 9
MAX DEV	10 -3	36 -83	14 -12	36 -67	19 -12	36 -57							19 -12	36 -83

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TABLE 6.4

Comparison of Percent Runoff Control Results for San Francisco, California

T, Treatment, Inches/Hour

S, Storage in Inches

Results of % Runoff Control	% Deviation from STORM
STORM	--
Statistical-Analytical	SA
Statistical-Events	SE

	.001		.002		.004		.006		.008		.010		Max Dev.	
.000	4 5 1	25 -75	9 10 6	11 -33	17 19 18	12 6	23 27 31	17 35	29 35 42	21 45	34 41 48	21 29	7 14	21 -75
.005	9 10 1	11 -89	14 14 7	0 -50									1 -8	11 -89
.010	11 14 2	27 -82	17 19 7	12 -59							42 49 49	17 0	3 -10	27 -82
.015	14 18 3	29 -64	19 23 10	21 -47									4 -11	29 -64
.020	15 22 8	47 -47	21 27 17	29 -19							47 56 52	19 11	9 -7	47 -47
.025	17 25 9	47 -47	23 31 18	35 -22									8 -8	47 -47
.030	18 28 12	56 -33	25 34 23	36 -8							52 62 55	19 6	10 -6	56 -33
.035	19 30 18	58 -5	27 37 24	37 -11									11 -3	58 -11
.040	20 32 22	40 10	28 40 32	43 14	39 49 34	26 -13					55 67 59	22 7	12 -5	40 14
.050	22 36 29	64 32	31 45 34	45 10									14 7	64 32
.060			33 49 37	48 12	45 58 43	29 -4					61 75 63	23 3	16 4	48 12
.070			35 52 38	49 9									17 3	49 9
.080			37 55 41	49 11	50 65 44	30 -12					65 81 68	25 5	18 -6	49 -12
.090			39 57 43	46 10									18 4	46 10
.100			40 59 48	48 20	54 70 54	30 0					69 85 70	23 1	19	48 20
.120					57 74 60	30 5					72 88 74	22 3	17 3	30 5
.140					59 77 65	31 10					75 91 77	21 3	18 6	31 10
.160					62 79 67	27 8					78 92 79	18 1	17 5	27 8
.180					64 80 70	25 9							16 6	25 9
.200					66 81 75	23 14							15 9	23 14
MAX DEV	14 -11	64 -89	19 -10	49 -59	18 9	31 14	4 8	17 35	6 13	21 45	16 14	25 29	19 14	64 -89

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TABLE 6.5

Comparison of Percent Runoff Control Results for Washington, D.C.

T, Treatment, Inches/Hour

S, Storage in Inches	.001		.002		.004		Max. Dev.	
.000	3 4 1	33 -67	6 8 2	33 -67	12 15 6	25 -50	3 -6	33 -67
.005	6 7 2	17 -67	9 11 3	22 -67			2 -6	22 -67
.010	8 10 3	25 -63	11 14 3	27 -73			3 -8	27 -73
.015	12 15 5	25 -58	13 17 4	31 -69			4 -9	31 -69
.020	13 17 5	31 -62	15 19 6	27 -60			4 -9	31 -60
.025	14 19 8	36 -43	17 22 9	29 -47			5 -8	36 -47
.030	16 21 10	31 -38	18 24 12	33 -33			6 -6	33 -38
.035	17 22 11	29 -35	20 26 13	30 -35			6 -7	30 -35
.040	20 25 11	25 -45	21 28 14	33 -33	28 36 17	29 -39	8 -11	33 -45
.050			24 32 21	33 -13			8 -3	33 -13
.060			27 35 28	30 4	33 44 32	33 -3	11 1	33 4
.070			29 38 32	31 10			9 3	31 10
.08			31 40 33	29 6	37 50 35	35 -5	13 2	35 6
.09			33 42 34	21 3			9 1	21 3
.10			35 44 36	26 3	41 55 38	15 -7	14 -3	26 -7
.12					45 59 42	31 -7	14 -3	31 -7
.14					47 62 49	32 4	15 2	32 4
.16					50 65 55	30 10	15 5	30 10
.18					52 67 58	29 12	15 6	29 12
.20					55 68 61	24 11	13 6	24 11
MAX DEV.	5 -8	36 -67	9 -9	33 -73	15 -11	33 -39	15 -11	36 -73

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Results of % Runoff Control	% Deviation from STORM
STORM	--
Statistical-Analytical	SA
Statistical-Moments	SM

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